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THE RADIO AFTERGLOW FROM THE GIANT FLARE OF SGR 1900+14: THE SAME MECHANISM AS AFTERGLOWS FROM CLASSIC GAMMA-RAY BURSTS?

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ABSTRACT

A radio afterglow was detected following the 1998 August 27 giant flare from the soft gamma repeater (SGR) 1900+14. Its short-lived behavior is quite different from the radio nebula of SGR 1806−20, but very similar to radio afterglows from classic gamma-ray bursts (GRBs). Motivated by this, we attempt to explain it with the external shock model as invoked in the standard theory of GRB afterglows. We find that the light curve of this radio afterglow is not consistent with the forward shock emission of an ultrarelativistic outflow, which is suggested to be responsible for the initial hard spike of the giant flare. Nevertheless, shock emission from a mildly or subrelativistic outflow expanding into the interstellar medium could fit the observations. The possible origin for this kind of outflow is discussed, based on the magnetar model for SGRs. Furthermore, we suggest that the presence of an ultrarelativistic fireball from SGR giant flares could be tested by rapid radio to optical follow-up observations in the future.

Subject headings: gamma rays: bursts — ISM: jets and outflows — stars: individual (SGR 1900+14)

1. INTRODUCTION

Soft gamma repeaters (SGRs) are generally characterized by sporadic and short (~0.1 s) bursts of hard X-rays with luminosities as high as 10^4 Eddington luminosity. They are also well known for two giant flares: the first on 1979 March 5 from SGR 0526−66 (Mazets et al. 1979) and the second on 1998 August 27 from SGR 1900+14 (Hurley et al. 1999). Frail, Kulkarni, & Bloom (1999) reported, following the giant 1998 August flare from SGR 1900+14, the detection of a transient radio source. Their observations covered the time from about one week to one month after the flare. The spectrum between 1 and 10 GHz is well fitted by a power law with $F_\nu \propto \nu^{-0.74\pm0.15}$. The source appears to have peaked at about a week after the burst and subsequently undergone a power-law decay with an exponent of $\alpha = -2.6 \pm 1.5$.

The initial hard spike of the August 27 flare has a duration of ~0.5 s and luminosity greater than 2×10^{44} ergs s^{-1} (>15 keV) if the source distance is $d \simeq 7$ kpc (Vasisht et al. 1994). The short duration, high luminosity, and hard spectrum indicate that a relativistically expanding fireball was driven from the star. The fireball should be relatively clean, and the Lorentz factor $\Gamma \gtrsim 10$ was inferred from the luminosity and the temporal structure (Thompson & Duncan 2001). With the experience of GRB afterglows, one may naturally ask whether this power-law fading radio afterglow is due to the blast wave emission driven by the fireball. Huang, Dai, & Lu (1998) and Eichler (2003) had made some discussions on the possible afterglow emission from SGRs. In this Letter, we try to explain the radio afterglow from this flare. We study the afterglow emission from the giant flare in § 2. We find that shock emission from an ultrarelativistic outflow fails to explain this radio afterglow. However, we propose that a mildly or subrelativistic outflow expanding into the interstellar medium could fit the observations. Finally, we discuss the possible origin for this kind of outflow in § 3.

2. RADIO AFTERGLOW FROM SGR GIANT FLARES

We consider that an outflow with "isotropic" kinetic energy E_0 and Lorentz factor Γ_0 ejected from the SGR expands into the ambient medium with a constant number density n. The interaction between the outflow and the surrounding medium is analogous to GRB external shock (Rees & Mészáros 1992; Mészáros & Rees 1997), but with quite different E_0 and Γ_0. The Sedov time at which the shock enters the nonrelativistic phase is roughly given by $t_{\rm nr} = (3E_0/4\pi n m_p c^5)^{1/3} = 1$ day $\times (E_{0,44}/n_0)^{1/3}$, where m_p is the proton mass and we used the usual notation $a \equiv 10^n a_n$. As the shock must have entered the nonrelativistic phase during the observation time of the radio afterglow from the giant flare, we develop a model that holds for both the relativistic and nonrelativistic phases. From the view of the energy conservation, the dynamic equation can be approximately simplified as (e.g., Huang, Dai, & Lu 1999; Wang, Dai, & Lu 2003)

$$(\Gamma - 1)M_0c^2 + (\Gamma^2 - 1)m_{\rm sw}c^2 = E_0, \tag{1}$$

where Γ is the Lorentz factors of the outflow, $m_{\rm sw} = (4/3)\pi R^3 m_p n$ is the mass of the swept-up interstellar medium (ISM) (R is the shock radius), and M_0 is the mass of the original outflow.

The kinematic equation of the ejecta is

$$dR/dt = \beta c/(1 - \beta), \tag{2}$$

where $v = \beta c$ is the bulk velocity of the outflow with $\beta(\Gamma) = (1 - \Gamma^{-2})^{1/2}$ and t is the observer time. If the outflow is beamed and sideways expansion with sound speed takes place, the expression of $m_{\rm sw}$ and the half-opening angle of the beamed outflow θ are, respectively, given by

$$\frac{dm_{\rm sw}}{dt} = 2\pi R^2(1 - \cos\theta)\frac{nm_p\beta c}{1 - \beta},$$
$$\frac{d\theta}{dt} = \frac{c_s(\gamma + \sqrt{\gamma^2 - 1})}{R}, \tag{3}$$

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where c_s is the sound speed and we use the approximate expression derived by Huang, Dai, & Lu (2000), which holds for both the ultrarelativistic and nonrelativistic limits.

Assuming that the distribution of the shock-accelerated electrons takes a power-law form with the number density given by $n(\gamma_e)d\gamma_e = K\gamma_e^{-p}d\gamma_e$ for $\gamma_m < \gamma_e < \gamma_M$, the volume emissivity at the frequency ν' in the comoving frame of the shocked gas is (Rybicki & Lightman 1979)

$$j_{\nu'} = \frac{\sqrt{3}q^3}{2m_e c^2}\left(\frac{4\pi m_e c\nu'}{3q}\right)^{(1-p)/2} B_\perp^{(P+1)/2} K F_1(\nu', \nu'_m, \nu'_M), \quad (4)$$

where q and m_e are, respectively, the charge and mass of the electron, $B_\perp$ is the strength of the component of magnetic field perpendicular to the electron velocity, ν'_m and ν'_M are the characteristic frequencies for electrons with γ_m and γ_M, respectively, and

$$F_1(\nu', \nu'_m, \nu'_M) = \int_{\nu'/\nu'_M}^{\nu'/\nu'_m} F(x)x^{(p-3)/2}dx, \quad (5)$$

with $F(x) = x\int_x^{+\infty} K_{5/3}(t)dt$ [$K_{5/3}(t)$ is the Bessel function]. The physical quantities in the preshock and postshock ISM are connected by the jump conditions (Blandford & McKee 1976): $n' = [(\hat{\gamma}\Gamma + 1)/(\hat{\gamma} - 1)]\,n$, $e' = [(\hat{\gamma}\Gamma + 1)/(\hat{\gamma} - 1)](\Gamma - 1)nm_pc^2$, where e' and n' are the energy and the number densities of the shocked gas in its comoving frame and $\hat{\gamma}$ is the adiabatic index, a simple interpolation of which between ultrarelativistic and nonrelativistic limits, $\hat{\gamma} = (4\Gamma + 1)/3\Gamma$, gives a valid approximation for trans-relativistic shocks.

Assuming that shocked electrons and the magnetic field acquire constant fractions (ϵ_e and ϵ_B) of the total shock energy, we get $\gamma_m = \epsilon_e[(p-2)/(p-1)](m_p/m_e)(\Gamma - 1)$, $B_\perp = (8\pi\epsilon_B e')^{1/2}$, and $K = (p-1)n'\gamma_m^{p-1}$ for $p > 2$. From the spectrum $F_\nu \propto \nu^{-0.74\pm0.14}$ of the radio afterglow, we infer that $p \simeq 2.5$. It is reasonable to believe that ν'_M, in comparison with the radio frequencies, is very large throughout the observations. The observer frequency ν relates to the frequency ν' in the comoving frame by $\nu = D\nu'$, where $D = 1/\Gamma(1 - \beta\cos\theta)$ is the Doppler factor. The observed flux density at ν is given by

$$F_\nu = V_{\rm eff}D^3 j_{\nu'}/4\pi d^2, \quad (6)$$

where $V_{\rm eff}$ is the effective volume of the postshock ISM from which the radiation is received by the observer and should be $V = m_{\rm sw}/n'm_p\Gamma^2$ for the isotropic case.

2.1. *Ultrarelativistic Outflow*

In terms of equations (1)–(3), we can obtain the dynamic evolution of the outflow, i.e., we get $\Gamma(t)$, $R(t)$, $m_{\rm sw}(t)$, and $\theta(t)$. Then using equation (4) and the expressions for $B_\perp$, K, and γ_m, we can get the evolution of the observed flux with time. The radio afterglow of the 1998 August flare peaks at about one week after the burst. In the relativistic shock model, it is required that the peak frequency ν_m cross the observation band at the peak time for optically thin synchrotron radiation. However, this can hardly be satisfied for a ultrarelativistic outflow with $\Gamma_0 \sim 10$, for reasonable values of the shock parameters and the medium density n. Instead, the model light curves generally peak at $t < 0.1$ day. This can be clearly seen in Figure 1, in which we plot the model light curves with different values of n and ϵ_B for both the isotropic and beamed outflow cases

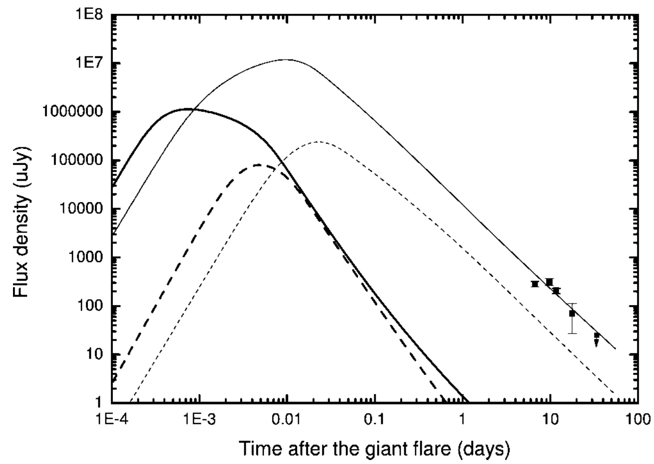

FIG. 1.—Comparison between the model light curves of the afterglows from ultrarelativistic outflows ($\Gamma_0 = 10$) with the observations of the radio flare from the August 27 giant flare of SGR 1900+14 observed at the frequency 8.46 GHz. Detections and upper limits for the nondetections, taken from Frail et al. (1999), are indicated by the filled squares and arrows, respectively. The thin solid and dashed lines represent the afterglows of isotropic outflows expanding into the ISM with $n = 1$ and 0.01 cm^{-3}, respectively. Other parameters used are $E_{\rm iso} = 10^{44}$ ergs, $\epsilon_e = 0.3$, $\epsilon_B = 10^{-5}$. The thick solid and dashed lines represent the afterglows of beamed outflows with $\theta_j = 0.15$ expanding into the ISM with $n = 1$ and 0.01 cm^{-3}, respectively. Other parameters are the same as thin lines.

and compare them with the observation data. Moreover, the peak flux F_{ν_m} are generally much larger than the observed peak flux. The reason can be easily understood from the following analytic estimate.

At the peak time $t \sim 10$ days of the radio afterglow, the shock had entered the nonrelativistic phase, so the radius of the shock is roughly $R \simeq (5/2)\beta ct$. From the condition of energy conservation $(4/3)\pi R^3(\beta^2/2)nm_pc^2 = E$, one can get $\beta = (12E/125\pi c^5t^3nm_p)^{1/5} = 0.16E_{44}^{1/5}t_1^{-3/5}n_0^{-1/5}$. The magnetic field is $B = (8\pi\epsilon_B e')^{1/2} = 1.4 \times 10^{-3}$ G $\epsilon_{B,-3}^{1/2}E_{44}^{1/5}t_1^{-3/5}n_0^{3/10}$, and the peak frequency and the peak flux are, respectively, given by

$$\nu_m = 3 \times 10^5 \text{ Hz} \left(\frac{\epsilon_e}{0.3}\right)^2 E_{44}^{3/5}t_1^{-9/5}n_0^{-1/10}\epsilon_{B,-3}^{1/2}, \quad (7)$$

$$F_{\nu_m} = \frac{N_eP_{\nu,m}}{4\pi d^2} = 4.4 \times 10^7 \ \mu\text{Jy}\, E_{44}^{4/5}t_1^{3/5}n_0^{7/10}\epsilon_{B,-3}^{1/2}, \quad (8)$$

where N_e is the total number of the swept-up electrons and $P_{\nu,m}$ is the peak spectral power (Sari, Piran, & Narayan 1998). It is clearly seen that ν_m can hardly be as large as $\nu_{\rm obs} = 8.46$ GHz for reasonable shock parameters of ϵ_e and ϵ_B (e.g., Granot, Piran, & Sari 1999; Wijers & Galama 1999; Panaitescu & Kumar 2002), and, furthermore, the peak flux is much larger than detected from the giant flare. Though this analytic estimate is for an isotropic outflow case, the beamed outflow has also this problem as shown in Figure 1.

Although the ultrarelativistic shock associated with the initial hard spike of the giant flare could not be responsible for the observed radio afterglow, we know from Figure 1 that its radio afterglow emission should be easily detected at the early time even for the beamed case. The optical afterglow emission from the ultrarelativistic shock is also calculated and shown in Figure 2. Clearly, early optical afterglow emission can be as bright as 100 μJy (R-band magnitude $m_R = 19$) at $t \lesssim 0.1$ day for

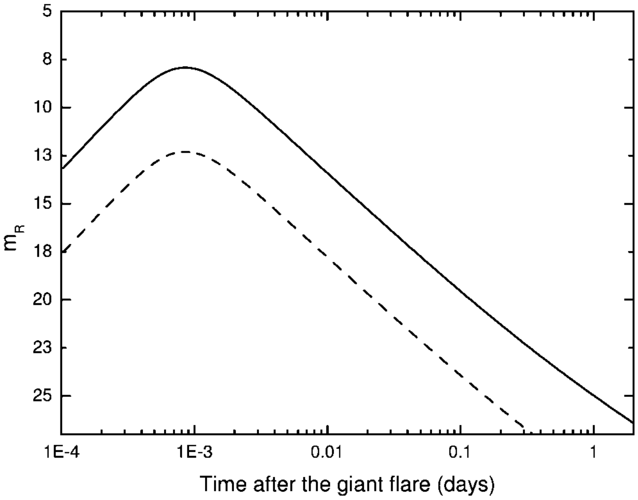

FIG. 2.—Predicted *R*-band ($\nu_R = 4.4 \times 10^{14}$ Hz) optical afterglow light curves of beamed ($\theta_j = 0.15$) and ultrarelativistic ($\Gamma_0 = 10$) outflows from SGR giant flares with $E_{\rm iso} = 10^{44}$ ergs, $n = 1$ cm^{-3}, and $\epsilon_e = 0.3$, but with different values for ϵ_B. The solid and dashed lines correspond to $\epsilon_B = 10^{-3}$ and 10^{-5}, respectively.

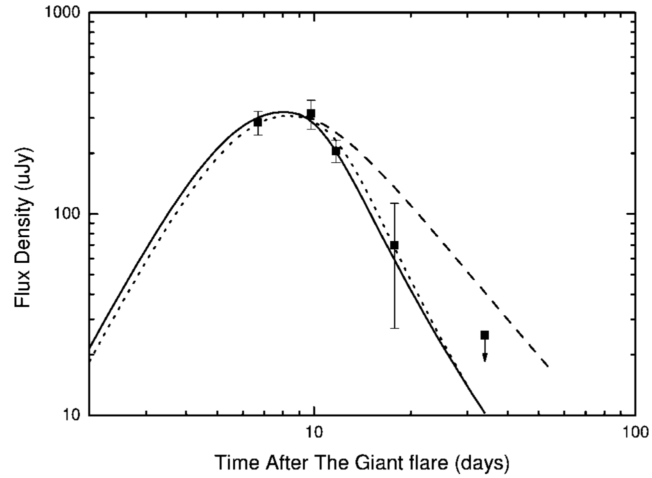

FIG. 3.—Fits of the radio (8.46 GHz) flare from the August 27 SGR giant flare with afterglow emission from beamed, mildly or subrelativistic outflow with isotropic energy $E_{\rm iso} = 10^{44}$ ergs and $\theta_j = 0.15$. The solid and dotted lines correspond to beamed outflows with sideways expansion expanding into the ISM with $n = 1$ cm^{-3} and $n = 0.01$ cm^{-3}, respectively. Other parameters used are ($\Gamma_0 = 1.033$, $\epsilon_e = 0.3$, $\epsilon_B = 0.008$) and ($\Gamma_0 = 1.13$, $\epsilon_e = 0.3$, $\epsilon_B = 0.03$), respectively. The dashed line has the same parameters as the solid line except that no sideways expansion is considered.

$\epsilon_B \gtrsim 10^{-3}$, a reasonable value we know from GRB afterglows. So we urge early follow-up radio-to-optical observations for future SGR giant flares to test the presence of ultrarelativistic outflows. Even at late times, $t \sim 10$ days, the fluxes at low radio frequencies are intense enough to be detected. At, say, $\nu = 150$ MHz, the extrapolated flux is 0.4 Jy from equations (7) and (8) for the typical parameters used.[3] The X-ray afterglow emission from the ultrarelativistic shock is, however, predicted to be lower than the detected bright and pulsed X-ray afterglow flux (Feroci et al. 2001), which is attributed to the emission from the neutron star surface immediately after the giant flare.

2.2. *Mildly or Subrelativistic Outflow*

Below we show that a mildly or subrelativistic forward shock is able to explain the observations. The reason is that for a mildly relativistic or subrelativistic outflow, it has a long enough period of coasting phase of the outflow, during which the flux increases with time even though $\nu_m \ll \nu_{\rm obs}$. After this coasting phase, the shock decelerates and the flux begins to fade in a power-law manner. For an isotropic outflow, the coasting phase lasts about

$$t \simeq \left(\frac{3E_0}{2\pi n m_p \beta_0^5 c^5}\right)^{1/3} = 5 \times 10^5 \text{ s } E_{0,44}^{1/3} n_0^{-1/3} \left(\frac{\beta_0}{0.4}\right)^{-5/3}, \quad (9)$$

until the mass of the ISM swept up by the blast wave is comparable to the mass of the outflow, where β_0 is the initial velocity of the outflow. During the coast phase, $\beta =$ const and $R = \beta t \propto t^1$. According to equations (4) and (6), $F_\nu \propto R^3\beta^{(5p-3)/2} \propto t^3$. When the mildly or subrelativistic outflow is decelerated by the swept-up mass, it quickly enters the Sedov phase, during which $\beta \propto t^{-3/5}$ and $R \propto t^{2/5}$. So, $F_\nu \propto t^{(21-15p)/10} \propto t^{-1.65}$ for $p = 2.5$. For a beamed outflow, the coasting phase is similar to the isotropic case, as the expansion is dominated by the cold ejecta during this phase. But during the deceleration phase, the shocked ISM plasma has comparable energy to initial energy E_0 and the sideways expansion may take place, so it is expected that the flux may decay more steeply than the isotropic case (e.g., Rhoads 1999; Sari, Piran, & Halpern 1999).

The fits with model light curves for mildly or subrelativistic, beamed outflows are presented in Figure 3, where the isotropic energy is chosen to be $E_{0,\,\rm iso} = 10^{44}$ ergs. We also present the model light curve for the same outflow but without sideways expansion, denoted by the dashed line. Clearly, the case without sideways expansion decays too slowly to fit the observations. In all these fits, we used fixed values for E, p, θ_j, ϵ_e, and n with only two free parameters: the initial Lorentz factor Γ_0 and ϵ_B. We can also obtain a nice fit to the observations for the case of a larger isotropic energy $E_{\rm iso}\theta_j^2/2 = 10^{44}$ ergs. In this case, the fitted parameters are ($n = 1$ cm^{-3}, $\Gamma_0 = 1.13$, $\epsilon_e = 0.3$, $\epsilon_B = 3 \times 10^{-6}$) and ($n = 0.01$ cm^{-3}, $\Gamma_0 = 1.4$, $\epsilon_e = 0.3$, $\epsilon_B = 1.5 \times 10^{-5}$) for different n. So the beamed outflow model can provide nice fits of the observations for a wide range of shock parameters such as n and E_0. We therefore conclude that the mildly or subrelativistic outflow from the SGR giant flare could provide a plausible explanation for this radio afterglow.

3. DISCUSSIONS AND CONCLUSIONS

We have shown that a mildly or subrelativistic outflow from the SGR could be consistent with this radio afterglow. This outflow is expected to originate from the neutron star crust, accompanying the giant flare. SGRs are now believed to be “magnetars,” neutron stars with surface field of order 10^{14}–10^{15} G or more (Duncan & Thompson 1992; Thompson & Duncan 1995). A magnetic field with $B > (4\pi\phi_{\rm max}\mu)^{1/2} \sim 2 \times 10^{14}(\phi_{\rm max}/10^{-3})^{1/2}$ G can fracture the crust, where $\mu \sim 10^{31}(\rho/\rho_{\rm nuc})^{4/3}$ ergs cm^{-3} is the shear modulus of the crust and $\rho_{\rm nuc}$ is the nuclear density and $\phi_{\rm max}$ is the yield strain of the crust. However, such a patch of crust is too heavy to be able to overcome the binding energy of the neutron star. We expect that only a tiny fraction of the fracturing crust matter can overcome the gravitational binding energy and is able to be accelerated to a mildly relativistic velocity $\Gamma_0 - 1 \sim 0.1$ by the released magnetic field energy. Note that the kinetic energy of the

[3] By using the formulae in Wang et al. (2000), we estimate that the synchrotron self-absorption frequency is below 10^7 Hz at this time.

mildly relativistic matter per unit of mass $(\Gamma_0 - 1)c^2$ is comparable to the binding energy GM_{NS}/R, where M_{NS} and R are the mass and radius of the neutron star, respectively. Let us denote the amount of matter as Δm, the isotropic kinetic energy E_0 and the real energy of the beamed outflow $E_r = E_0\theta_j^2/2$, where θ_j is the beaming angle of this outflow. For $\Gamma_0 - 1 \sim 0.1$, $\Delta m = 5 \times 10^{22}E_{r,43}$ g $= 5 \times 10^{23}E_{0,44}\theta_j^2$ g. Let the size of this patch of matter be Δr. Because of the insensitivity of Δr on Δm for the outermost crust of neutron star, we estimate $\Delta r \simeq 0.1$–0.3 km for $E_r \simeq 10^{42}$–10^{44} ergs.

Once we know Δr, we can estimate the beaming angle θ_j of the outflow when it breaks away from the confinement of the magnetic field. This amount of matter will be vaporized and become plasma near the neutron star surface, which moves out along the open field lines of the magnetar. The initial kinetic energy density of this outflow is $\varepsilon_{k0} = \dot{E}_r/(A_0\beta_0 c) = 1.6 \times 10^{24}$ ergs cm^{-3} $\dot{E}_{r,43}(\Delta r/2\ \mathrm{km})^{-2}(\beta_0/0.4)^{-1}$, where $\dot{E}_r$ is the real kinetic energy luminosity of this outflow, $\beta_0 c$ is the initial velocity of this outflow, and A_0 is the initial sectional area. As the plasma moves out to radial radius r, the sectional area $A = \pi(r\sin\theta)^2$, where θ is the angle relative to the magnetic axis. Because the magnetic field lines satisfy $r \propto \sin^2\theta$, $A \propto r^3$ for small θ and $\varepsilon_k \propto r^{-3}$. On the other hand, the magnetic field energy density scales with r as $\varepsilon_B = (B_0^2/8\pi)(r/R)^{-6}$, where B_0 is the surface magnetic field of the neutron star. When the magnetic field energy density decreases to be comparable to the kinetic energy density, the outflow plasma breaks from the confinement of the magnetic field. This corresponds to a radius $r_b/R \simeq (B_0^2/8\pi\varepsilon_{k0})^{1/3} \simeq 30B_{0,15}^{2/3}\dot{E}_{r,43}^{-1/3}(\beta_0/0.4)^{1/3}(\Delta r/0.2\ \ \mathrm{km})^{2/3}$ and $\theta_b/\theta_0 \simeq (r/R)^{1/2} \simeq 5.5B_{0,15}^{1/3}\dot{E}_{r,43}^{-1/6}(\beta_0/0.4)^{1/6}(\Delta r/0.2\ \ \mathrm{km})^{1/3}$. Note that θ_b, which is roughly equal to the beaming angle θ_j, is very insensitive to the value of E_r. As the initial opening angle near the neutron star surface $\theta_0 = \Delta r/R = 0.02(\Delta r/0.2\ \mathrm{km})$, we estimate the beaming angle of the outflow is $\theta_j \simeq 0.1$–0.2 for typical parameters.

What powers the ejection of this patch of matter? We think that the reconnection of the magnetic field within a region of size Δr during the period of the giant flare will release energy of $(B^2/8\pi)(\Delta r)^2 V_A \Delta t \sim (B^2/8\pi)(\Delta r)^2 R$, which should be equal to $\Delta m(\Gamma_0 - 1)c^2$, where B is the crust magnetic field, V_A is the internal Alfvén velocity, and Δt is the growth time of the instability causing the giant flare, viz., the duration ($\Delta t \simeq 0.5$ s) of the initial hard spike of the August 27 giant flare (Thompson & Duncan 1995, 2001). The size is therefore estimated to be $\Delta r \sim 0.2$ km, and the mass is $\Delta m \sim 10^{23}B_{15}^2$ g, which are in reasonable agreement with the above estimates according to the light curve fits if $E_0 \sim 10^{45}$ ergs or equally $E_r \sim 10^{43}$ ergs.

Note that continuing acceleration of electrons at the surface of the neutron star is also a possible mechanism for the radio afterglow, and needs further careful investigation in future.

In summary, we studied the afterglow emission from the possible ultrarelativistic outflow and mildly or subrelativistic outflow accompanying the SGR giant flares. The radio afterglow emission from the August 27 giant flare of SGR 1900+14 is consistent with a mildly or subrelativistic outflow but could not be produced by the forward shock emission from an ultrarelativistic outflow. However, we predict that this ultrarelativistic outflow, suggested to be associated with the hard spike of the giant flare, if it exists, should produce bright radio to optical afterglows at the early phase ($t \lesssim 0.1$ days), which can be tested by future observations.

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